Rainfall Timing and Poultry Litter Application Rate Effects on Phosphorus Loss in Surface Runoff

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ABSTRACT

Phosphorus (P) in runoff from pastures amended with poultry litter may be a significant contributor to eutrophication of lakes and streams in Georgia and other areas in the southeastern United States. The objectives of this research were to determine the effects of litter application rate and initial runoff timing on the long-term loss of P in runoff from surface-applied poultry litter and to develop equations that predict P loss in runoff under these conditions. Litter application rates of 2, 7, and 13 Mg ha^{-1}, and three rainfall scenarios applied to 1- × 2-m plots in a 3 × 3 randomized complete block design with three replications. The rainfall scenarios included (i) sufficient rainfall to produce runoff immediately after litter application; (ii) no rainfall for 30 d after litter application; and (iii) small rainfall events every 7 d (5 min at 75 mm h^{-1}) for 30 d. Phosphorus loss was greatest from the high litter rate and immediate runoff treatments. Nonlinear regression equations based on the small plot study produced fairly accurate (r^2 = 0.52–0.62) prediction of P concentrations in runoff water from larger (0.75 ha) fields over a 2-yr period. Predicted P concentrations were closest to observed values for events that occurred shortly after litter application, and the relative error in predictions increased with time after litter application. In addition, previously developed equations relating soil test P levels to runoff P concentrations were ineffective in the presence of surface-applied litter.

Over the past decade, control of nonpoint-source pollution has come to the forefront in efforts to improve water quality in the United States and elsewhere. The principal components of agricultural nonpoint-source pollution are sediment, bacteria, N, and P. Of these, P is the element most commonly associated with accelerated eutrophication in freshwater systems because these systems are usually P limited (Correl, 1998).

The state of Georgia is one of the top broiler chicken (*Gallus gallus domesticus*) producing regions of the United States with 1.29 billion broilers raised in 2002 (National Agricultural Statistics Service, 2002). Besides broiler production, agriculture in central and northern Georgia is generally limited to beef cattle and hay production. Thus, broiler, cattle, and hay production are often integrated, and broiler litter (manure and bedding) serves as an organic fertilizer on pastures and hayfields. Traditionally, broiler litter is applied to meet forage N needs, but surface application greatly increases the risk of P loss in surface runoff because of low (2:1) N to P ratio. Forms of P in runoff include dissolved inorganic and organic P forms and particulate P associated with mineral or organic particles transported in runoff. Because erosion rates from hayfields and pastures are low, the dissolved fraction is usually the dominant form of P in runoff from hayfields and pastures (Sharpley et al., 1992).

A strong relationship exists between the rate of manure application and the concentration of total phosphorus (TP), dissolved reactive phosphorus (DRP), and particulate P in runoff (McLeod and Hegg, 1984; Mueller et al., 1984; Edwards and Daniel, 1994; Vervoort et al., 1998; Wood et al., 1999; Pote et al., 2001; Kleinman and Sharpley, 2003) where P concentrations in runoff typically increase with an increase in manure application rate. The majority of the published research shows that most of the P is lost in the first runoff event from fields where manure has been surface-applied (Edwards et al., 1994; Sharpley, 1997; Sauer et al., 1999). Several researchers have shown that after an initial spike, P concentration in runoff declines with time or number of rainfall events, often remaining greater than background concentration for an extended period (Heathman et al., 1995; Sharpley, 1997). In a multiple-year study, Pierson et al. (2001) reported increased P concentration in runoff from natural rainfall for up to 18 mo after an application of poultry litter to a small watershed in Georgia. In contrast, some small plot studies have shown P concentrations in runoff were similar to background concentrations after two artificial rainfall events (Edwards and Daniel, 1994; Sauer et al., 1999).

Because most of the P lost from manure applications is lost in the first runoff event, several researchers investigated the effect of time between manure application and a runoff-producing rainfall on P loss. Several small plot or lab studies have shown a decrease in P concentration with an increase in time to a runoff-producing rainfall event with liquid poultry manure (Westerman and Overcash, 1980) or incorporation of poultry litter into the soil (Sharpley, 1997). However, when dry poultry litter is surface-applied to pastures and hayfields, a surface layer of thatch is likely to prevent direct contact between the litter and the soil, reducing the possibility that P in the manure will be adsorbed immediately by the soil. Edwards et al. (1994) found that time to artificial rainfall producing runoff (4–14 d) had no effect on either the concentration or mass of ortho-P or TP in runoff. In a more recent study, Pierson et al. (2001) observed that P concentrations from 0.75 ha were less than 5 mg L^{-1} DRP for intervals of up to 7 mo and greater

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Abbreviations: DRP, dissolved reactive phosphorus; R1, sufficient rainfall to produce 30 min of runoff immediately after litter application; R2, no rainfall for 30 d after manure application, then sufficient rainfall to produce 30 min of runoff; R3, small rainfall events every 7 d (5 min at 75 mm h^{-1}) for 30 d and then sufficient rainfall to produce 30 min of runoff; STP, soil test phosphorus; TP, total phosphorus; WSP, water-soluble phosphorus.

than 5 mg L^{-1} DRP when events occurred within 12 d of poultry litter application.

The objectives of this research were twofold. The first was to determine the effects of application rate and initial runoff timing on the long-term loss of P from poultry litter surface-applied to pastures and hayfields. The second was to develop equations that may be used to predict P loss from surface-applied poultry litter and evaluate the effectiveness of these equations with runoff data from a reference site.

MATERIALS AND METHODS

Experimental Design

To determine the effect of manure application rate and initial runoff timing on P loss, we employed three poultry litter application rates and three runoff scenarios. Poultry litter application rates were 2, 7, and 13 Mg ha^{-1} (typical application rates in northern Georgia). Rainfall scenarios included: (i) sufficient rainfall to produce 30 min of runoff immediately after litter application (R1); (ii) no rainfall for 30 d after manure application, then sufficient rainfall to produce 30 min of runoff (R2); and (iii) small rainfall events every 7 d (5 min at 75 mm h^{-1}) for 30 d and then sufficient rainfall to produce 30 min of runoff (R3). Simulated rainfall was applied to each plot at a rate of 75 mm h^{-1} with a standard rainfall simulator and experimental protocol (Humphry et al., 2002). These scenarios were chosen based on the contradictory nature of previous research related to timing to first runoff event. The third runoff scenario is unlike any previously reported and we believe it to be the most realistic. Based on almost 30 yr of weather data from the Athens, GA, area, the probability that 25 mm of rain will fall on any single day is approximately 7% and the probability of receiving 50 mm of rain on any given day is less than 4%. However, the probability that 6 mm of rain will fall on a given day is about 18%. Based on these probabilities, it seemed more realistic to expect that after manure application some small rainfall events will occur before an event large enough to produce runoff.

The three litter rates and rainfall scenarios were applied to 1- × 2-m plots in a 3 × 3 randomized complete block design with three replications. In addition to these treatments, three control plots were included (one for each block) to allow for correction of P loss not associated with litter application. Therefore, the experiment consisted of thirty plots (3 × 3 × 3 + 3 = 30). Following the implementation of the initial rainfall scenarios, all plots received sufficient rainfall to produce 30 min of runoff on a biweekly basis for 5 mo from May through October 2001. Due to several days of unseasonably warm weather in January 2002, we had the opportunity to conduct additional rainfall simulations on the 13 Mg ha^{-1} plots and control plots.

The experimental site was a hayfield with a fairly uniform 8% slope at the University of Georgia Plant Sciences Farm near Athens, GA. The soil in the study area is a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludults) with average pH of 5.7 and Mehlich III–extractable P of 22 mg kg^{-1} in the A horizon. In late February 2001, 'Kentucky 31' tall fescue (*Festuca arundinacea* Schreb.) was planted on the site to supplement the relatively thick stand of fescue present. At that time, 14–3–12 (N–P–K) starter fertilizer was applied at a rate of 448 kg ha^{-1}. Approximately 48.5 mm of natural rain fell on the experimental area between February and May.

From 3 Mar. to 1 May 2001, thirty 1- × 2-m plots were installed at the site in three blocks of 10 plots. The blocks were positioned so that the long axis of all plots was oriented down slope. Plot borders, consisting of 15-cm-tall, approximately 0.3-cm-thick sheet metal, were pressed into the ground to a depth of at least 7 cm to isolate runoff. Aluminum flumes were installed at the down-slope edge of each plot to divert surface runoff to a collection point. The litter used in this study was collected on 10 May 2001 from a broiler farm in northern Georgia. Poultry litter was applied by hand on 14, 15, and 16 May to plots in Blocks 1, 2, and 3, respectively.

During artificial rainfall simulations, collection of runoff from the field plots began after steady runoff commenced and continued for 30 min. Runoff was collected in toto, and a 500-mL subsample was taken and immediately placed on ice. Clear polymer covers were placed over each plot between simulations to prevent the plots from receiving natural rainfall. These covers consisted of polyethylene film stretched over wooden frames that were pitched to direct rainwater away from the plots. Wooden blocks, 10 cm tall, were used to support the covers above the plots. This resulted in a gap of at least 10 cm at each end of the plot. Paired thermocouples (in and out of the plot) installed in five plots showed that the soil temperature under the covers differed from ambient soil temperature by less than 0.5°C throughout the experiment. All plots were mowed to a height of approximately 10 cm every 2 wk for the duration of the experiment, and clippings were removed to prevent the loss of P to runoff from the decaying grass. Local well water was used as the water source (P concentration < 0.01 mg L^{-1}). After the last rainfall event, soil samples (composites of 10 random samples) were collected from the 0- to 10-cm depth within each plot.

Sample Analysis

Soil samples were collected from the surface 10 cm of each plot following the final runoff event. Samples were air-dried and ground to pass a 2-mm sieve. Soil pH was determined in a 1:2 soil to water mixture using a glass electrode. Water-soluble and Mehlich III–extractable P was determined (Mehlich, 1984; Pote et al., 1996). Total P in unfiltered runoff samples was determined colorimetrically (Murphy and Riley, 1962) following micro-Kjeldahl digestion (Baker and Thompson, 1992). Immediately after collection, 125 mL of each runoff sample was filtered (0.45-μm pore diameter) to remove particulate matter and stored at −20°C until analyzed. The DRP concentration of filtered runoff water samples was also determined colorimetrically (Murphy and Riley, 1962).

Total P content of the poultry litter was determined colorimetrically following micro-Kjeldahl digestion (Baker and Thompson, 1992). Water-soluble phosphorus (WSP) in poultry litter was determined colorimetrically after shaking 20 g of manure in 4 L of deionized water for 4 h. Total P, water-soluble P, pH, and moisture content of the poultry litter were 23.98 g kg^{-1}, 6.2 g kg^{-1}, 8.46, and 54.2%, respectively. The pH of the litter was determined in a 1:5 litter to water mixture using a glass electrode. Litter moisture content was determined after oven-drying at 65°C for 48 h.

Reference Site

Data used to assess the effectiveness of P loss prediction equations presented as "observed" data were originally collected and reported by Pierson et al. (2001). In the Pierson et al. (2001) study, five fescue–common Bermudagrass [*Cynodon dactylon* (L.) Pers.] fields (0.72–0.79 ha) were bordered by earthen berms and fitted with H-flumes and Isco (Lincoln, NE) refrigerated samplers. Soil series present at the Eatonton, GA, sites include Cecil, Altavista (fine-loamy, mixed, semiactive, thermic, Aquic Hapludults), Helena (fine, mixed, semiactive, thermic Aquic Hapludults), and Sedgefield (fine, mixed, active, thermic Aquultic Hapludalfs). Precipitation and runoff volume were recorded at 5-min intervals. During the two years studied, poultry litter was applied four times: 16 Mar. 1995 (102 kg P ha^{-1}), 30 Oct. 1995 (112 kg P ha^{-1}), 4 Mar. 1996 (174 kg P ha^{-1}), and 25 Sept. 1996 (103 kg P ha^{-1}). Litter samples were analyzed for TP and WSP by Kuykendall et al. (1999) by the same methods used in the present study. Runoff samples were filtered (0.45 μm) and analyzed for DRP by the molybdate blue method (Murphy and Riley, 1962). Thirty-nine runoff events from the reference site from 1 Jan. 1995 to 31 Dec. 1996 were used as observations for modeling purposes. The initial Mehlich-I soil test phosphorus (STP) level reported by Pierson et al. (2001) of 13 mg kg^{-1} was converted to 25 mg kg^{-1} Mehlich III (Mehlich, 1984; Shuman et al., 1988).

Because runoff P concentration can be strongly influenced by P associated with the soil, as well as P from surface-applied litter, any attempt to model P loss must include some estimate of the P contribution from the soil P pool. The contribution of P from the soil P pool, estimated by STP, was modeled with the following equation (Schroeder et al., 2004), which describes the relationship between STP (mg kg^{-1}) and P in runoff from similar soils:

$$\text{DRP (mg L}^{-1}) = (0.0018 \times \text{Mehlich III}) + 0.15 \quad [1]$$

Statistical Analysis

Total and soluble P mass losses from each plot were calculated for each runoff event using P concentration and runoff volume. Overall total P loss and cumulative P losses by runoff event were calculated. Average TP and DRP losses from control plots were subtracted from treatment plot P loss so that only P loss associated with litter application would be analyzed. Statistical analyses were performed using the Statistical Analysis System (SAS Institute, 1994). Analysis of variance (ANOVA) techniques were used to determine treatment effects and to check for interaction across all 10 runoff events. The least significant difference method was used to separate treatment means. Nonlinear regression was used to develop predictive equations relating P loss in runoff from surface-applied poultry litter to P application rate, runoff depth, cumulative rainfall, days since manure application, antecedent soil water content, and temperature. Regression analysis was also employed to determine if STP levels were related to P application rate, runoff depth, cumulative rainfall, or pH.

To evaluate modeling performance, the following measures were used: correlation coefficient (r), a measure of the linear correlation between observed and simulated results; root mean square error (RMSE), an estimate of the inherent error in the simulation; and the relative RMSE (RRMSE = RMSE/observed mean × 100), a measure of error in relation to the mean. In addition to the above analysis, we also regressed observed against simulated results and analyzed the intercepts and slopes to determine if they were different from 0 and 1, respectively (SAS Institute, 1994).

RESULTS AND DISCUSSION

Rainfall and Litter Treatment Effects

Analysis of variance for TP and DRP in runoff across all runoff events revealed significant interaction between treatments and runoff events. However, for individual runoff events treatment effects were significant ($p < 0.01$), and there was no interaction between litter rate and rainfall scenario. Therefore, each biweekly runoff event was analyzed as an independent experiment to assess treatment effects.

Cumulative TP and DRP loss were greatest from the treatment (R1) with artificial rainfall producing runoff almost immediately after litter application (Table 1).

Table 1. Total phosphorus (TP) and dissolved reactive phosphorus (DRP) lost from each of 10 runoff events and percentage of total lost in each event for rainfall treatments R1 (immediate rainfall), R2 (no rainfall for 30 d), and R3 (several small rainfall events before runoff) averaged across all litter rates.

	R1		R2		R3	
Event	Amount	Percentage of total	Amount	Percentage of total	Amount	Percentage of total
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
			TP			
1	4.41a†	59.59	2.37b	51.52	1.61b	39.46
2	1.10a	14.86	0.49b	10.65	0.45b	11.03
3	0.39a	5.27	0.33a	7.17	0.47a	11.52
4	0.34a	4.59	0.48a	10.43	0.62a	15.20
5	0.34a	4.59	0.20a	4.35	0.14a	3.43
6	0.23a	3.11	0.24a	5.22	0.34a	8.33
7	0.17a	2.30	0.17a	3.70	0.12a	2.94
8	0.16a	2.16	0.13a	2.17	0.14aa	3.43
9	0.15a	2.03	0.12a	2.61	0.11a	2.70
10	0.11a	1.49	0.10a	2.17	0.08a	1.96
Total	7.40A‡		4.63B		4.08B	
			DRP			
1	3.22a	57.30	1.84b	48.94	1.28c	37.87
2	0.85a	15.12	0.44b	11.70	0.41b	12.13
3	0.28a	4.98	0.28a	7.45	0.38a	11.24
4	0.26a	4.63	0.42a	11.17	0.52a	15.38
5	0.29a	5.16	0.11a	2.93	0.11a	3.25
6	0.18a	3.20	0.21a	5.59	0.32a	9.47
7	0.15a	2.67	0.15a	3.99	0.12a	3.55
8	0.14a	2.49	0.13a	3.46	0.09a	2.66
9	0.14a	2.49	0.11a	2.93	0.10a	2.96
10	0.11a	1.96	0.07a	1.86	0.05a	1.48
Total	5.62A		3.76B		3.38B	

† Means in the same row followed by the same lowercase letter are not different according to LSD ($p < 0.05$).
‡ Totals in the same row followed by the same uppercase letter are not different according to LSD ($p < 0.05$).

The other treatments (R2 and R3) did not produce significantly different cumulative TP or DRP losses ($p = 0.05$). The fact that the most realistic initial rainfall treatment (R3) produced less cumulative TP and DRP loss (4.08 and 3.38 kg ha^{-1}, respectively) than R1 (7.40 and 5.62 kg ha^{-1}, respectively) suggests that under "real world" conditions (R3) P losses from surface-applied manure may be considerably less than the "worst case" scenario (R1). The effect of rainfall timing was most pronounced in the first runoff event where the R1 treatment showed both the greatest TP and DRP loss (4.41 and 3.22 kg ha^{-1}, respectively) and the highest percentage P loss (59.6 and 57.3%, respectively). The R3 treatment produced the smallest TP and DRP loss as well as the smallest percent TP and DRP losses in the first event. Over the remainder of the events there was little difference in P loss or percentage P loss among the rainfall treatments.

The fact that cumulative P loss was not different between the treatments with and without small, non-runoff producing rainfall events (R2 and R3) suggests that the initial application of small amounts of rain may have had two contrasting effects. First, the small rainfalls probably leached some soluble P from the manure lying on the surface and transported it into the soil where it was adsorbed by reactive soil surfaces. Conversely, the wet and dry periods between the small rainfall events may have stimulated mineralization of organic P (Grierson et al., 1999), thereby negating some of the adsorption effects. Thus, no differences were observed between the treatments.

As expected, the 13 Mg ha^{-1} litter treatments produced much higher cumulative TP and DRP loss than the 2 or 7 Mg ha^{-1} treatments (Table 2). The greatest litter application rate produced the greatest TP and DRP loss for all individual runoff events (Table 2). The first runoff event showed the most dramatic differences among the three litter application rates with the 13, 7, and 2 Mg ha^{-1} rates producing TP losses of 4.8, 2.4, and 1.3 kg ha^{-1}, and DRP losses of 3.6, 2.0, and 0.7 kg ha^{-1}, respectively. By the second runoff event, P losses from all three treatments decreased considerably to 1.4, 0.5, and 0.3 kg ha^{-1} TP and 1.0, 0.4, and 0.3 kg ha^{-1} DRP. For the second and later events DRP losses from the 7 and 2 Mg ha^{-1} treatments were not significantly different.

Average TP and DRP losses in runoff from the 13 Mg ha^{-1} poultry litter treatments for the additional rainfall simulations conducted in January 2002 were 0.3 and 0.2 kg ha^{-1}, respectively. These values were somewhat higher than those seen in the 10th rainfall event when TP and DRP losses of 0.18 and 0.15 kg ha^{-1}, respectively, were observed for the 13 Mg ha^{-1} poultry litter treatment (Table 2). We attribute the increase in P loss in these final runoff events to higher runoff volume due to wetter antecedent soil moisture conditions. The fact that the 13 Mg ha^{-1} poultry litter treatment was still producing relatively high levels of both TP and DRP after 10 mo shows the long-term effects of surface application of poultry litter at high rates ($\geq$13 Mg ha^{-1}). In fact, Pierson et al. (2001) observed DRP concentrations in excess of 1 mg L^{-1} for more than 18 mo following 4 yr of poultry litter application.

The fact that after 10 runoff events only 11.2, 6.2, and 5.7% of applied P was lost from the 2, 7, and 13 Mg ha^{-1} litter treatments, respectively, combined with the relatively modest increases in STP (reported below), indicates that a significant portion of the applied P remained on or very near the soil surface. This residual surface P will continue to solubilize over time and may produce

Table 2. Total phosphorus (TP) and dissolved reactive phosphorus (DRP) lost from each of 10 runoff events and percentage of total lost in each event for the three litter rates averaged across all rainfall treatments.

Event	2 Mg ha^{-1} poultry litter		7 Mg ha^{-1} poultry litter		13 Mg ha^{-1} poultry litter	
	Amount	Percentage of total	Amount	Percentage of total	Amount	Percentage of total
	kg ha^{-1}	%	kg ha^{-1}	%	kg ha^{-1}	%
				TP		
1	1.26b†	61.17	2.38b	56.40	4.75a	49.17
2	0.28b	11.65	0.45b	10.66	1.35a	13.98
3	0.13b	6.31	0.27b	6.40	0.79a	8.18
4	0.22b	10.68	0.41b	9.72	0.81a	8.39
5	0.05b	2.43	0.16b	3.79	0.48a	4.97
6	0.08b	3.40	0.24b	5.69	0.49a	5.07
7	0.03b	1.46	0.01b	0.31	0.29a	3.00
8	0.02b	0.49	0.10b	2.37	0.28a	2.90
9	0.03b	1.46	0.11b	2.61	0.24a	2.48
10	0.02b	0.97	0.09b	2.13	0.18a	1.86
Total	2.12C‡		4.22B		9.66A	
				DRP		
1	0.72c	47.37	2.03b	55.62	3.59a	47.24
2	0.28b	18.42	0.39b	10.68	1.04a	13.68
3	0.12b	7.89	0.19b	5.21	0.63a	8.29
4	0.19b	12.50	0.35b	9.59	0.66a	8.68
5	0.03b	1.97	0.10b	2.74	0.39a	5.13
6	0.08b	5.26	0.20b	5.48	0.42a	5.53
7	0.03b	1.97	0.12b	3.29	0.26a	3.42
8	0.02b	1.32	0.10b	2.74	0.25a	3.29
9	0.03b	1.97	0.10b	2.74	0.21a	2.76
10	0.02b	1.32	0.07b	1.92	0.15a	1.97
Total	1.52C		3.65B		7.60A	

† Means in the same row followed by the same lowercase letter are not different according to LSD ($p < 0.05$).
‡ Totals in the same row followed by the same uppercase letter are not different according to LSD ($p < 0.05$).

elevated P levels in runoff for a significant period (Pierson et al., 2001).

The results of this experiment both affirm and contradict previous research on P loss following poultry litter application. It is quite clear from our research that a 30-d delay between litter application and runoff significantly reduced both the initial TP and DRP loss and the overall mass of P lost when compared with runoff immediately following manure application. These results appear to agree with results published by Westerman and Overcash (1980) and Sharpley (1997). However, these two studies differ from the present study in that they either used liquid manure (Westerman and Overcash, 1980) or incorporated the manure into the soil (Sharpley, 1997). These two differences would probably amplify the delay effect because of the close contact between soil and manure. Contradictory findings were reported by Edwards et al. (1994), who concluded that delay intervals of 4, 7, and 14 d did not affect TP and DRP loss in runoff from poultry litter surface-applied to fescue plots. They reasoned that delay interval did not affect P loss because the grass cover limited contact between the litter and the soil (i.e., conditions were not optimal for soil adsorption of litter P). The differences between the Edwards et al. (1994) study and the present study are probably due to several factors, including the shorter delay interval (14 vs. 30 d), lower litter application rate (5.6 vs. 13 Mg ha^{-1}), and the fact that Edwards et al. (1994) did not include an immediate runoff treatment in their study. It is possible that the delay effect occurs in a short period due to rapid adsorption of P, so that without an immediate runoff treatment, this effect is not observed.

Soil Phosphorus Levels

After the final rainfall event, soil samples were collected from the upper 10 cm of each plot (Table 3). Soil pH ranged from 5.6 to 5.9, deionized water–extractable P ranged from 0.3 to 6.8 mg kg^{-1}, and Mehlich III–extractable P ranged from 21.8 mg kg^{-1} for the unamended controls to 65.9 mg kg^{-1} for the 13 Mg ha^{-1} treatment. Changes in Mehlich-III STP were related to the total phosphorus in the litter (LTP) applied (R^2 = 0.57) by the following equation:

$$\text{Mehlich III} = 22.9 + 0.18\ (\text{LTP kg ha}^{-1}) \qquad [2]$$

Based on the above equation, poultry litter application at the reference site should have increased Mehlich-III STP levels to approximately 200 mg kg^{-1}. However, Pierson et al. (2001) reported Mehlich-III equivalent levels of only 155 mg kg^{-1}. The poor agreement between observed and predicted STP values was partly due to the fact that the soil sampling depth used by Pierson et al. (2001) was 15 cm, whereas soils were only sampled to 10 cm in the current study.

Due to the relatively small amount of P extracted by deionized water (mean = 2.80 mg kg^{-1}) and the high degree of variability (standard deviation = 3.10 mg kg^{-1}) within treatments, no significant relationships were found between deionized water–extractable P and any of the independent variables used.

Table 3. Surface horizon pH and P extracted by deionized water and Mehlich III averaged by treatment in samples taken after last runoff event.

Treatment: Rain†	Treatment: Litter‡	pH	Deionized water–extractable P (mg kg^{-1})	Mehlich III–extractable P (mg kg^{-1})
1	1	5.92a§	1.48ab	27.82b
1	2	5.84a	1.77ab	34.43b
1	3	5.93a	6.81a	63.60a
2	1	5.63a	2.49ab	35.43b
2	2	5.76a	3.41ab	46.64b
2	3	5.88a	3.44a	65.92a
3	1	5.79a	2.24ab	33.68b
3	2	5.69a	0.72ab	31.33b
3	3	5.73a	5.29a	57.84a
1	control	5.70a	0.30b	21.76b

† Rain refers to the rainfall scenario employed (1, immediate runoff; 2, no rainfall for 30 d; 3, several small rainfall events before runoff).
‡ Litter refers to the litter rate (1, 2 Mg ha^{-1}; 2, 7 Mg ha^{-1}; 3, 13 Mg ha^{-1}).
§ Means (n = 3) followed by the same letter are not significantly different ($p < 0.05$).

Curve Fitting

The contribution of surface-applied poultry litter to P loss from small plots was best described by a first-order decay equation:

$$P_t = (P_0 A)\exp(-kt)$$

where P_t is the concentration of P lost in runoff (mg L^{-1}) at time t and P_0 is the litter total P or water-soluble P application rate (kg ha^{-1}). The terms A and k are constants related to the maximum P concentration predicted and the effect of time since litter application, respectively. The principle of conditional error (Bose, 1949; Milliken and Johnson, 1984) was used to determine if one equation would adequately describe the relationship between P loss and time for all treatments. This analysis indicated that there were significant differences ($p < 0.05$) between the three rainfall treatments and that separate equations were needed. Throughout the fitting process attempts were made to include factors such as rainfall, runoff, temperature, soil moisture, and days since litter application in the equation. Of all these factors, inclusion of time since application alone resulted in functional equations. As a result, the following 12 equations were developed:

- R1

$$TP_t = (TP_0 \times 0.231)\exp(-0.041t) \qquad [3]$$

$$DRP_t = (TP_0 \times 0.118)\exp(-0.042t) \qquad [4]$$

$$TP_t = (WSP_0 \times 0.890)\exp(-0.041t) \qquad [5]$$

$$DRP_t = (WSP_0 \times 0.690)\exp(-0.042t) \qquad [6]$$

- R2

$$TP_t = (TP_0 \times 0.159)\exp(-0.030t) \qquad [7]$$

$$DRP_t = (TP_0 \times 0.114)\exp(-0.027t) \qquad [8]$$

$$TP_t = (WSP_0 \times 0.619)\exp(-0.030t) \qquad [9]$$

$$DRP_t = (WSP_0 \times 0.443)\exp(-0.027t) \qquad [10]$$

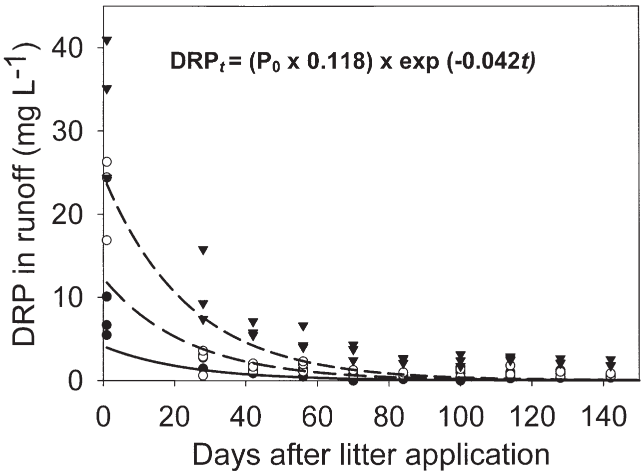

Fig. 1. Typical plot showing runoff dissolved reactive phosphorus (DRP) concentration (mg L^{-1}) as predicted with Eq. [4], for 2 (solid line), 7 (long dash), and 14 (short dash) Mg ha^{-1} litter applications and observed P in runoff for 2 (●), 7 (○), and 14 (▼) Mg ha^{-1} litter applications to 1- × 2-m plots.

- R3

$$TP_t = (TP_0 \times 0.116) \exp(-0.024t) \quad [11]$$

$$DRP_t = (TP_0 \times 0.080) \exp(-0.021t) \quad [12]$$

$$TP_t = (WSP_0 \times 0.450) \exp(-0.024t) \quad [13]$$

$$DRP_t = (WSP_0 \times 0.309) \exp(-0.021t) \quad [14]$$

The coefficients related to the number of days since litter applications were similar for the R2 and R3 equations. However, the k values for the R1 equations significantly were larger than the k values of the other treatments. The larger k values for the R1 equations represent the effect of runoff occurring immediately after litter application. The fact that the k values for both the R2 and R3 equations are smaller than the k for the R1 equations indicates that, in the absence of runoff, as the number of days since application increases, P loss in runoff decreases. This effect may be due to immobilization of P in the litter over time as previously discussed. However, in soils with high STP levels, this effect may be less apparent because of reduced soil P sorption capacity.

In these equations the first term, P_0A, represents the maximum P concentration in runoff when t is zero. The value of A in the equations for the R3 treatment is about half the value of A in the equations for the R1 treatments. This reflects the combined effect of the delay in runoff and the application of small rainfall events before runoff. Figure 1 shows the decay equation for TP and DRP developed for the R1 and R3 scenarios. The best fit was obtained for the R1 equations followed by the R3 equations (Table 4).

Predicting Dissolved Reactive Phosphorus Loss

Since DRP loss Eq. [4] and [6] and [12] and [14] produced the best fit to the data from the small plot study reported above and also represented the worst- and best-case scenarios, respectively, they were used to predict DRP loss from litter applications at the reference site.

Table 4. Statistical parameters associated with P loss prediction equations.

Treatment†	Equation	P form‡	R^2	RMSE§
				mg L^{-1}
R1	[3], [5]	TP	0.91	2.93
	[4], [6]	DRP	0.91	2.30
R2	[7], [9]	TP	0.75	1.65
	[8], [10]	DRP	0.71	1.38
R3	[11], [13]	TP	0.86	1.13
	[12], [14]	DRP	0.82	0.95

† R1, immediate rainfall; R2, no rainfall for 30 d; R3, several small rainfall events before runoff.
‡ TP, total phosphorus; DRP, dissolved reactive phosphorus.
§ Root mean square error.

There was little difference in the accuracy of prediction of DRP concentration with either set of equations (Fig. 2, Table 5). The RRMSE values for all equations were greater than 84%, indicating that the average predicted DRP concentration had an error equal to 84% of the mean observed DRP concentration. Regression analysis revealed that the slopes and intercepts of Eq. [12] and [14] were significantly less than one and greater than zero, respectively. This indicates that Eq. [12] and [14] generally tended to underpredict DRP concentration in runoff.

The prediction of runoff DRP loss by any of the four equations was more accurate than predictions using only the STP vs. DRP relationship (Eq. [1]). The five initial runoff events of 1995 (Fig. 3) reflect the DRP concentration in runoff before the initial litter application. Based on an estimated initial Mehlich-III STP of 25 (mg kg^{-1}), Eq. [1] predicted a DRP concentration of 0.20 mg L^{-1}. The average observed DRP concentration for these five events was 0.33 mg L^{-1}, indicating that Eq. [1] somewhat underestimated DRP concentration. However, based on Mehlich-III STP levels of 67, 110, 164, and 205 mg kg^{-1} (predicted with Eq. [2]) for the four litter applications, respectively, Eq. [1] predicted DRP concentrations of 0.27, 0.35, 0.46, and 0.52 mg L^{-1}. For runoff events that occurred within a few days of litter application, these predicted DRP concentrations accounted for only around 10% of the observed P concentration and overall under-

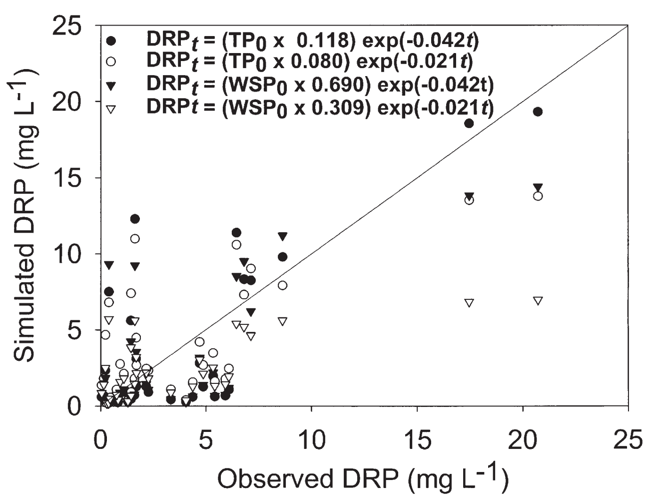

Fig. 2. The relationship between observed and simulated dissolved reactive phosphorus (DRP) concentration (mg L^{-1}) for Eq. [4] (●), [6] (▼), [12] (○), and [14] (▽). The solid line represents a 1:1 relationship.

Table 5. Root mean square error (RMSE), relative root mean square error (RRMSE), intercept, slope, correlation coefficient (r), and number of observations (n) for the prediction of dissolved reactive phosphorus (DRP) concentration in runoff from the reference site by Eq. [4], [6], [12], and [14].

DRP variable	RMSE	RRMSE	Intercept	Slope	r^2	n
	mg L^{-1}		mg L^{-1}			
Eq. [4]	3.3	84.7	0.18	0.89	0.62	39
Eq. [6]	3.3	84.3	0.54	0.69*	0.55	39
Eq. [12]	3.3	84.8	1.40*	0.62*	0.52	39
Eq. [14]	3.8	97.3	1.17*	0.31*	0.47	39

* Indicates significantly different from zero (intercept) or one (slope) at $p = 0.05$.

predicted average DRP concentration by approximately 5 mg L^{-1}. The general ineffectiveness of the STP to DRP relationship to predict DRP concentration indicates that such relationships may not be suitable for predicting P loss in the presence of surface-applied litter.

To further explore the sources of variation between observed and predicted DRP concentrations, individual events were plotted (Fig. 3 and 4). With any of the four equations, predicted DRP concentrations for runoff events that occurred soon after litter application were closer to observed values than predictions for runoff events that occurred many months after litter application. For events within 15 d of litter application, Eq. [4] and [6] tended to overpredict P loss. However, Eq. [12] and [14] tended to overpredict P loss as the time since litter application increased (Fig. 3 and 4). This is because Eq. [12] and [14] were developed from plots that had delayed runoff. The effect of the delayed runoff was a lower slope on the decay equation allowing for higher P loss as the number of days since litter application increased. The underprediction was most pronounced with several large-volume runoff events where DRP concentration actually increased compared with the previous event. The fact that DRP concentration increased as runoff volume increased in the absence of additional P inputs seems counterintuitive, but was observed repeatedly in the reference site data.

Overall, Eq. [4] was most accurate when runoff occurred within 15 d of litter application and Eq. [12] was most accurate when runoff occurred more than 15 d after litter application. However, due to the highly variable nature of the observed runoff P concentration, none of the equations was very effective in predicting P losses overall. In fact the equations using WSP as the measure of initial litter P content (Eq. [6] and [14]) performed worse than the equations that used TP as the measure of initial litter P. Interestingly, Vadas et al. (2004) recently reported that predictive equations using water-extractable P concentration in manure and the amount of rain water that interacts with the manure were very accurate in predicting soluble P loss from surface-applied manure under laboratory conditions.

The above discussion implies that observed DRP concentration did not follow a predictable decrease over time following litter applications. Since the prediction equations used in this study were classic decay equations, they could not predict these increases in DRP concentration. The question follows, Why does the DRP concentration increase in the absence of added P, and why did the increased concentrations coincide with large volume runoff events? We propose two possible explanations that may be related.

First, variable source area (VSA) may play a role in this phenomenon. The concept of VSA is that for any given field there is a limited area that contributes run-

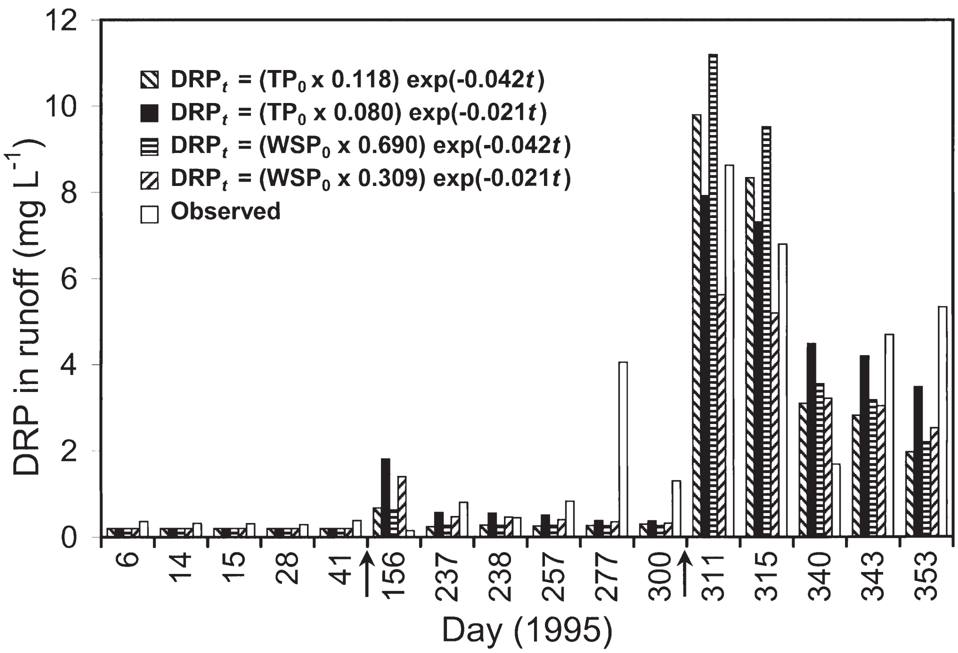

Fig. 3. Dissolved reactive phosphorus (DRP) concentration (mg L^{-1}) observed and simulated for runoff events in 1995. Arrows indicate the approximate dates when poultry litter was applied. The terms TP and WSP refer to total and water-soluble phosphorus content of litter, respectively, and t is the number of days since litter application.

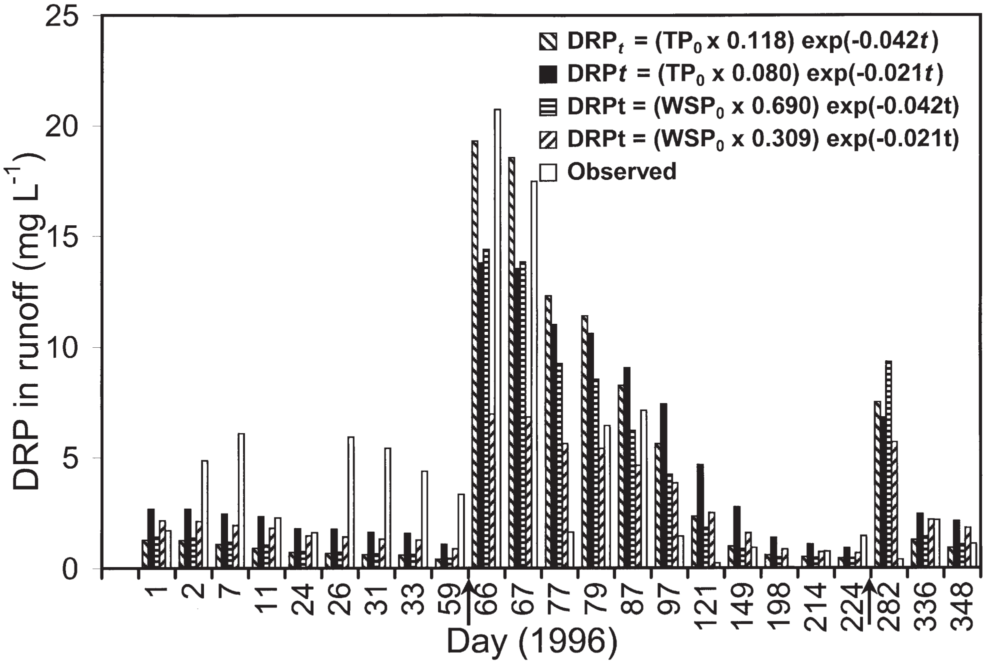

Fig. 4. Dissolved reactive phosphorus (DRP) concentration (mg L^{-1}) observed and simulated for runoff events in 1996. Arrows indicate the approximate dates when poultry litter was applied. The terms TP and WSP refer to total and water-soluble phosphorus content of litter, respectively, and *t* is the number of days since litter application.

off to a stream and that the size of this area changes over time (Dunne and Black, 1970). The size of the source area depends on the size of the storm, antecedent moisture, topography, and soil type. Based on the VSA concept, increases in DRP concentration could be due to the larger source area supplying runoff during larger storms. In effect, frequent small storms remove P from the same area, thereby depleting the soluble P pool. This results in a decrease in DRP concentration over time. However, when a large storm occurs, the VSA increases and areas that may have a large pool of soluble P contribute to runoff, increasing DRP concentration in runoff. Alternatively, the small, low DRP concentration events may be the result of overland flow from very small areas close to the collection flumes.

Second, microbial biomass turnover due to prolonged soil desiccation during periods without rain and rapid rewetting during rainfall events may contribute significantly to the size of the soluble P pool in the VSAs. In a study of C and N fluctuations, Van Gestel et al. (1993) observed that desiccation and rewetting contributed to C and N mineralization. Kieft et al. (1987), who studied microbial response to rapid increases in water potential, reported that 17 to 58% of soil biomass C was released on rapid wetting of dry soils. They concluded that a rapid water potential increase could be a potent catalyst for the turnover of soil C, as well as other nutrients such as N and P. More recently, Turner and Haygarth (2001) reported increases in water-extractable soil P of 185 to 1900% on drying and rewetting, which they attributed to microbial cell lysis. The P in cellular components, such as phospholipids and nucleic acids, that are released on cell lysis may pass through the typical 0.45-μm filter used to differentiate dissolved P from particulate P. Several studies have shown that organic P may be hydrolyzed by and react with molybdate (Ron Vaz et al., 1993; Tarapchak, 1993; Haygarth et al., 1997). In effect, the increases in DRP observed may be partly due to a flux of dissolved organic P released from lysed microbial cells.

In addition to the above-mentioned phenomena, some of the lack of model fit is probably related to the difficulties encountered when applying a model developed from small plot data to data from larger scales.

CONCLUSIONS

When runoff-producing rainfall was applied immediately following litter application, significantly greater TP and DRP losses ($p < 0.05$) were measured for the first runoff event. It appears that rainfall timing (i.e., time to first runoff event) and litter application rate have a dramatic effect on P loss in runoff. Additionally, after 10 runoff events P losses in runoff were still significant and resulted in P concentrations exceeding 1 mg L^{-1}, the value that has been proposed as the maximum desirable P concentration in agricultural runoff. Total mass of P lost from all 10 runoff events represented 6 to 11% of the P applied, indicating that a significant pool of litter P remained after 10 events. Most of this P pool may be organic P that remains on the soil surface rather than inorganic P adsorbed to the soil since only modest increases were seen in STP levels. Additionally, an equation relating litter P application rate to changes in Mehlich-III STP explained about 60% of the variability in Mehlich-III STP.

Nonlinear regression equations that may be useful in predicting P losses in runoff from surface-applied poultry litter were developed. These equations were able to explain 68 to 91% of the variability seen in P losses. Because the levels of P loss seemed to rebound after several months as reflected in the runoff from the January 2002 rainfall simulations, future research in this area should be directed at determining the effect of the interval between runoff events on P loss. The results indicate that the equations developed in this study were reasonably effective in predicting DRP loss from poultry litter that was surface-applied to the pastures and hayfields at the reference site and may be of use elsewhere under similar conditions. This prediction was most accurate for runoff events that occurred soon after litter application, which consequently are the events that produce the greatest DRP loss. The largest source of variation between observed and simulated DRP concentration was associated with instances where observed DRP concentration increased in the absence of additional P application. These counterintuitive increases in DRP concentration may be explained by a combination of processes including variable source area and microbial turnover. The results of this study also indicate that in the presence of surface-applied manure the use of equations that relate P in runoff to STP may not be appropriate. Additionally, further study of the dynamics of P cycling in the surface horizon and thatch layer of soils where poultry liter has been applied should be pursued.

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